An Impact-Location Estimation Algorithm for Subsonic Uninhabited Aircraft

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ABSTRACT

An impact-location estimation algorithm is being used at the NASA Dryden Flight Research Center to support range safety for uninhabited aerial vehicle flight tests. The algorithm computes an impact location based on the descent rate, mass, and altitude of the vehicle and current wind information. The predicted impact location is continuously displayed on the range safety officer's moving map display so that the flightpath of the vehicle can be routed to avoid ground assets if the flight must be terminated. The algorithm easily adapts to different vehicle termination techniques and has been shown to be accurate to the extent required to support range safety for subsonic uninhabited aerial vehicles. This paper describes how the algorithm functions, how the algorithm is used at NASA Dryden, and how various termination techniques are handled by the algorithm. Other approaches to predicting the impact location and the reasons why they were not selected for real-time implementation are also discussed.

NOMENCLATURE

|	
Cd	coefficient of drag
d	drift distance, ft
F	force, lbf
FTS	flight termination system
Fx	force in the x-axis direction, lbf
Fy	force in the y-axis direction, lbf
Fz	force in the z-axis direction, lbf
g	gravity constant, 32.2 ft/sec^2
GRIM	global real-time interactive map
H	ground altitude, ft
ILEA	impact-location estimation algorithm
m	vehicle mass in its terminated state, slug
M	wind magnitude, ft/sec
RSO	range safety officer
S	drag reference area, ft^2
T	descent time, sec
UAV	uninhabited aerial vehicle
V	descent velocity (true velocity), ft/sec
x	distance traveled to the east, ft
y	distance traveled to the north, ft
ρ	standard day density, slug/ft^3
θ	wind direction, deg

INTRODUCTION

The NASA Dryden Flight Research Center has recently been conducting several programs involving uninhabited vehicles (fig. 1). In general, these vehicles are designed to operate subsonically at altitudes higher than 50,000 ft. These vehicles tend to have long wing spans resembling gliders. Most of the vehicles fly with less than 20 lbf/ft^2 wing loading. A variety of propulsion systems are used on these vehicles, including jet engines, turbo-charged internal combustion engines, and solar electric motors.

These vehicles are currently being flown in restricted airspace over Edwards Air Force Base, California, where NASA Dryden resides as a tenant. History has shown the accident rate of uninhabited vehicles to be greater than that of piloted aircraft. Consequently, care must be exercised in the operation of such vehicles to minimize risk to other assets, whether on the ground or in the air. All uninhabited aircraft operated at NASA Dryden that have the potential of violating range boundaries are required to contain a flight termination system (FTS).[1-3] The purpose of the FTS is to ensure that the vehicle does not leave the designated airspace or range if normal command and control are lost. The location where the terminated vehicle would impact the ground is also important because the airspace in which these vehicles
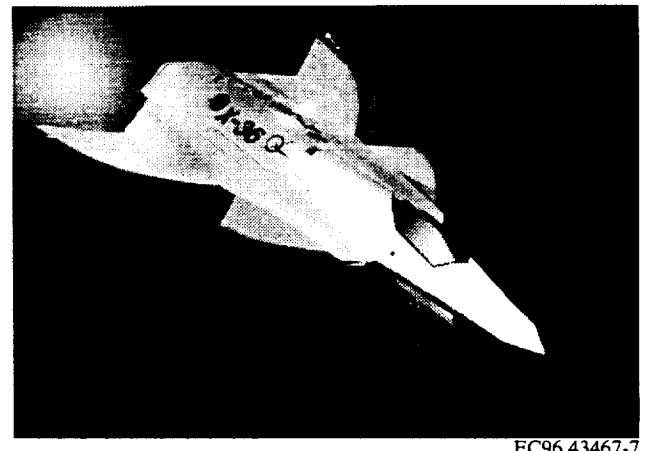

EC95 43261-1
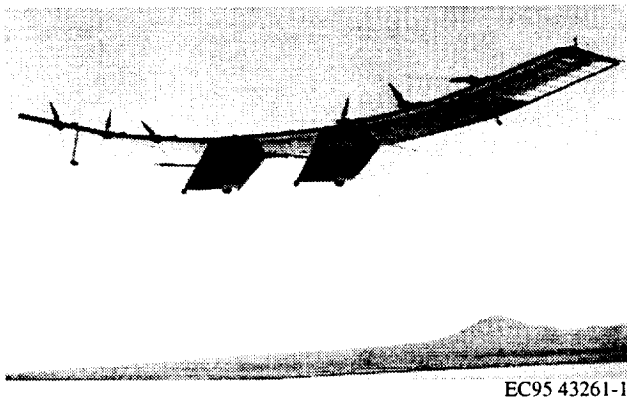
(a) The Pathfinder vehicle.

EC96 43488-1
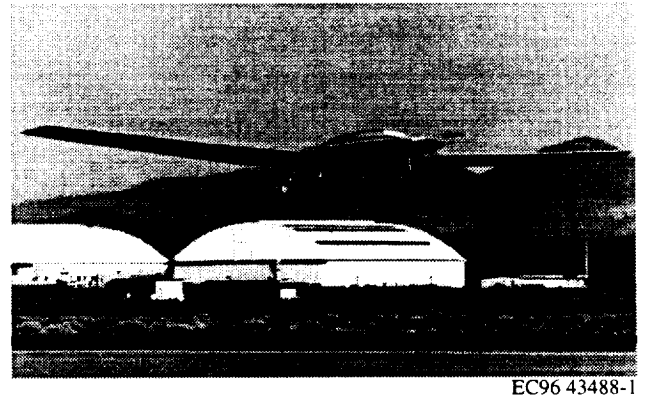
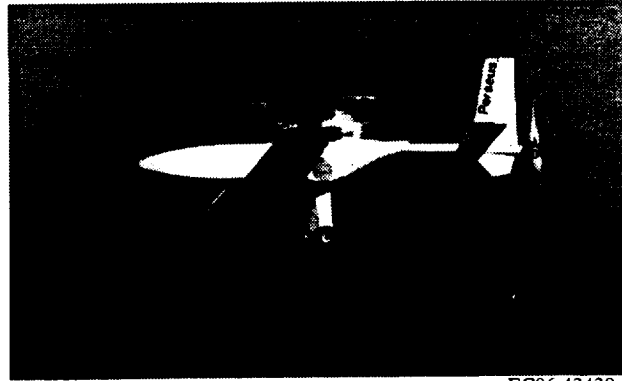(b) The Darkstar vehicle.

EC96 43707-4

(c) The Altus I vehicle.

EC96 43467-7

(d) The X-36 vehicle.

Figure 1. Representative UAVs at NASA Dryden that use the ILEA.

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EC96 43439-5

(e) The Perseus B vehicle.

Figure 1. Concluded.

operate is above high-value ground assets. A means of predicting where a terminated vehicle will impact is critical for real-time flightpath management.

Algorithms in use at other range facilities[4,5] are designed for high-kinetic-energy vehicles, but NASA Dryden needed an algorithm that accounted for low-speed (low-kinetic-energy) vehicles. The algorithm would be required to operate in real time, be flexible in its ability to account for a variety of termination techniques, and provide a reasonable estimate of impact location. Therefore, NASA Dryden has developed and incorporated an algorithm that provides a continuous prediction of where the vehicle will impact in the event the termination system is activated. Although the actual impact location is important, the direction of drift in the terminated state can be of more importance. The impact-location estimation algorithm (ILEA) takes into account vehicle information, including current altitude, its mass when terminated, descent rate, and wind data. The present location and predicted impact location of the vehicle provide the range safety officer (RSO) with enough information to instruct the uninhabited aerial vehicle (UAV) operator where to fly in order to minimize the chances of damaging ground assets in the event of a termination.

The ILEA is one of many techniques available to the RSO for assuring range safety and is integrated into the NASA Dryden global real-time interactive map (GRIM) display.[6] The GRIM is an advanced moving map display that provides information such as the present location, altitude, speed, heading, and range boundaries of the vehicle. For UAV operations, additional operational boundaries, referred to as UAV keep-out zones (fig. 2), can be displayed. These zones are typically drawn around high-value ground assets. During the flight, the RSO provides guidance to the vehicle operator regarding the vehicle flightpath in order to prevent the predicted impact point from entering these regions.

This paper describes the algorithm, how various termination techniques are handled by the algorithm, and how the algorithm is used at NASA Dryden. Other approaches to predicting the impact location, why these approaches were not selected for real-time implementation, how the algorithm performed during a mission, and how the algorithm would have performed in an off-design case are also discussed. The algorithm has presently been adapted by several UAV operators for use in their command and control facilities and has been included in the real-time displays by other ranges.

Figure 2. UAV keep-out zones in the Edwards AFB area.

ASSUMPTIONS AND MODEL

The algorithm is an approximation, so the RSO must provide sufficient margin near assets to account for the uncertainties of the ILEA. Descent characteristics may not be well known, and emergency situations that require flight termination are often full of surprises. The following assumptions are used in the model.

- **The descent rate of the vehicle in the terminated state is known.**

- **The vehicle remains intact and descends as a single mass.** Components of the aircraft that descend separately are not modeled. An attempt is made to determine what the most massive component would be, and that piece is modeled. The less massive pieces are assumed to represent less of a range safety hazard. The impact location is displayed as a discrete point rather than a debris field, although it is understood that the vehicle pieces will not all impact at the same point. Different vehicles and termination techniques will result in different debris patterns. When large pieces are expected to result from a termination, the vehicle flightpath is carefully planned to include a reasonable amount of scatter about the predicted impact point for the unmodeled pieces.

- **The vehicle speed or kinetic energy along the flightpath dissipates quickly. Any distance traveled as a result of the flight speed is not significant and can be ignored.** For pieces of the vehicle that break off or for a destruct-type system, the forward motion is also ignored. Because such pieces are very unlikely to be dynamically stable, it is assumed that the pieces will have an effective lift-to-drag ratio of zero. Also, the kinetic energy of any such pieces should be low and thus not significantly contribute to drift distances.

- **The vehicle engines or motors stop operating upon termination.**

- **Standard day altitude densities from the** U.S. Standard Atmosphere, 1962[7] **are used for the calculations.** Although atmospheric conditions are typically different from standard day,

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analysis has shown that use of the standard day data is reasonable. Actual densities from two days when missions were conducted were used, and the results were compared to standard day data. The resulting impact locations differed by approximately 1 percent. The standard day assumption is reasonable because flight testing of these vehicles typically occurs in good weather. If an operation is expected to occur in all-weather situations, actual day densities would provide better results.

- **The time for the termination system to activate is small and can be ignored.** A finite amount of time is needed for the termination system to activate and for the vehicle to reach terminal velocity, but these events are not modeled by the ILEA.

- **Vehicle midflight weight is used to compute vehicle mass.** The exact weight of the vehicle at termination cannot be determined in advance. If accurate information regarding the vehicle fuel usage is available, weight could be updated throughout the mission; however, weight updating is not currently done. Thus, midflight weight for the mission is normally used to compute the vehicle mass.

- **The vehicle is not accelerating in the vertical plane (terminal velocity is assumed for the descent).**

- **The vehicle in the terminated condition moves with the air mass (winds).**

- **The downrange motion of a spinning or uncontrolled vehicle will be small.** For vehicles that descend in an uncontrolled fashion, forward motion can also be ignored. The direction of motion is reasoned to be random in nature, and the net result will be insignificant when compared to the effects of drift caused by winds. Some vehicles descend in a spin. Although a spin can be a stable flight mode with a nonzero lift-to-drag ratio, predicting the heading of any downrange travel is well beyond current capabilities.

- **The winds do not change between updates.** Wind data can often be hours old, depending on the frequency of updates. If winds change substantially between updates, the impact location would not be accurately predicted.

The ground is modeled as 2372 ft, which corresponds to the main runway altitude at Edwards Air Force Base. The ILEA is based on the model of a vehicle descending under parachute. The descent rate is thus characterized by a parachute drag coefficient, the parachute reference area, and vehicle mass in its terminated configuration.

Figure 3 shows the physics modeled. Because the vehicle is assumed to be not accelerating in the vertical plane, the sum of the forces acting on it are zero. Drag is thus equal to weight where

$$\mathrm{drag} = \frac{1}{2} \times \rho \times V^2 \times Cd \times S \qquad (1)$$

$$\mathrm{weight} = m \times g \qquad (2)$$

Wind data can be the largest source of error in the algorithm. Wind data are obtained from weather balloons launched prior to and throughout the mission. These data are used by the algorithm to predict the downwind drift during the descent and are contained in a separate file referred to as the "winds file." In general, data from the balloon are available in 1000-ft increments. Another option for obtaining wind information involves deriving wind estimates from the UAV onboard navigation systems during the mission.
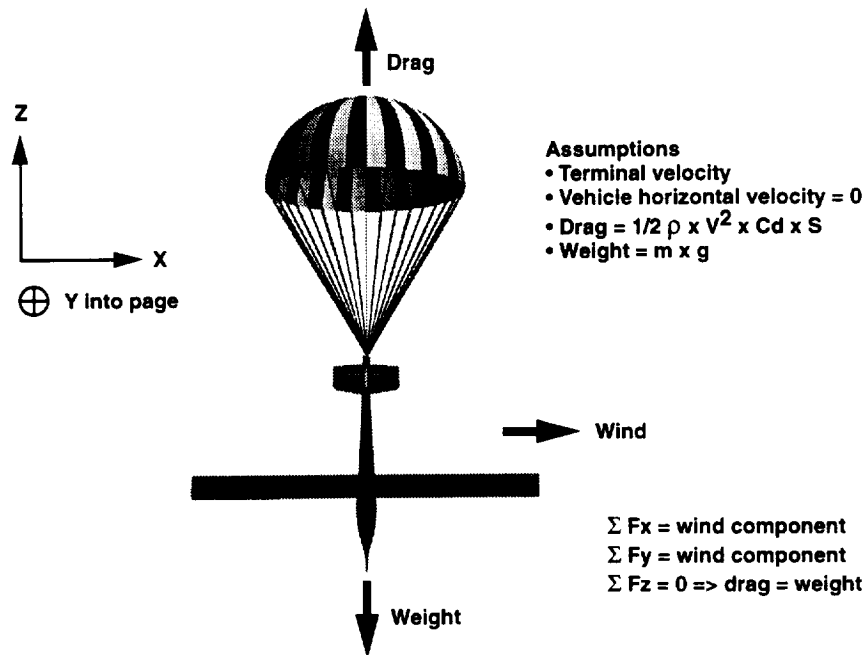
Figure 3. Free-body diagram of modeled system.

Figure 4 shows a simplified flowchart of the code. Beginning at ground level and using an altitude step size of 1000 ft, an average altitude above the ground is determined. The descent rate at this median altitude is computed by solving equations (1) and (2) for descent velocity, V. From this computed descent rate, the time to descend through the altitude band is computed. The wind magnitude and direction at the center of the altitude band is computed from the data provided in the winds file. The impact location is repositioned downrange based on the time in the altitude band, magnitude of the wind, and direction of the wind computed for the current altitude band. The sequence is then repeated by incrementing the altitude until the vehicle altitude is reached.

Figure 5 shows how the impact location is displayed in real time. The predicted impact location is constantly displayed, even after the termination system is activated, if aircraft altitude data are available.

The ILEA exists in real-time and batch versions. Appendix A shows a copy of one of the batch versions of the ILEA. Inputs required are the weight of the vehicle in its terminated state (mass is computed in the algorithm from the weight), the equivalent parachute drag coefficient and its associated reference area, wind magnitude and direction as a function of altitude, and the current altitude of the vehicle. In its current implementation at NASA Dryden, the real-time version obtains altitude from radar-tracking data. Other implementations could use telemetered data or altitude transponders from the aircraft.

APPLICATION OF ALGORITHM TO VARIOUS TERMINATION TECHNIQUES

The algorithm is able to adapt to a variety of termination techniques. Figure 6 shows several common termination techniques employed by UAVs. The technique shown in figure 6(a), descent under a main
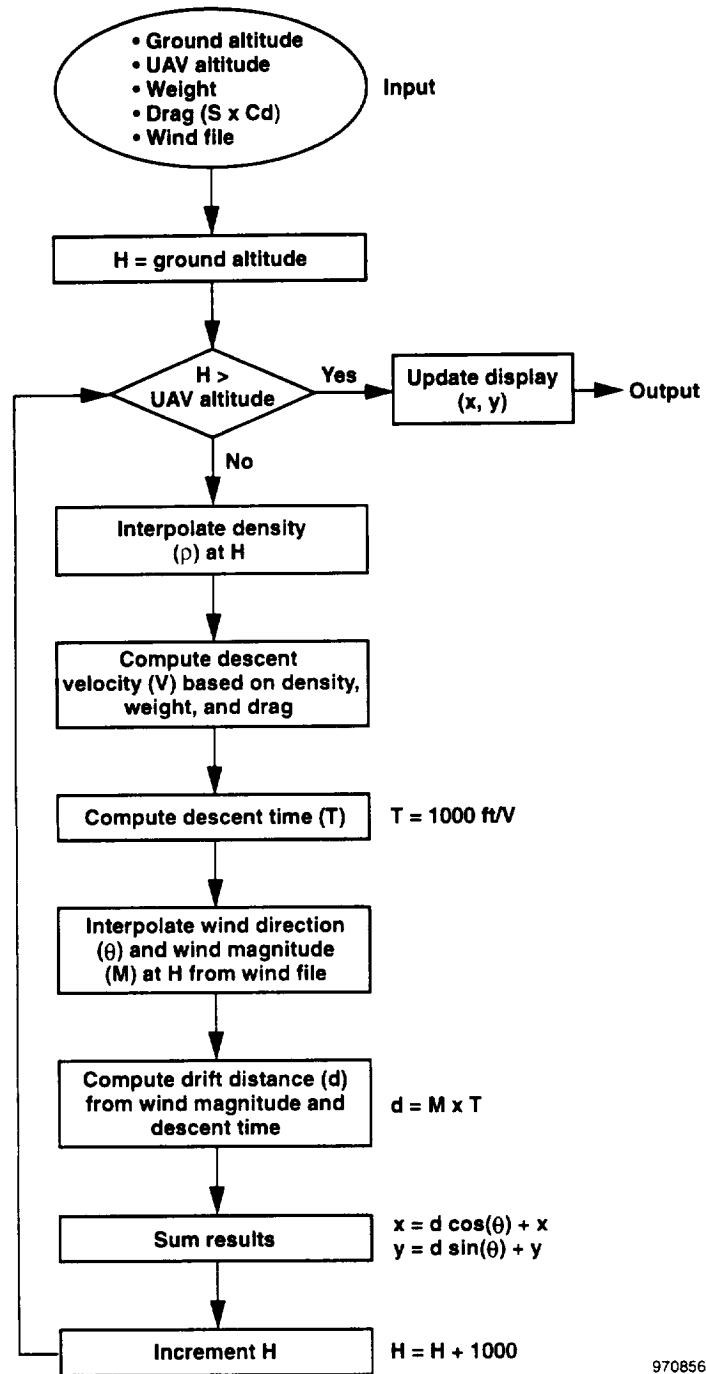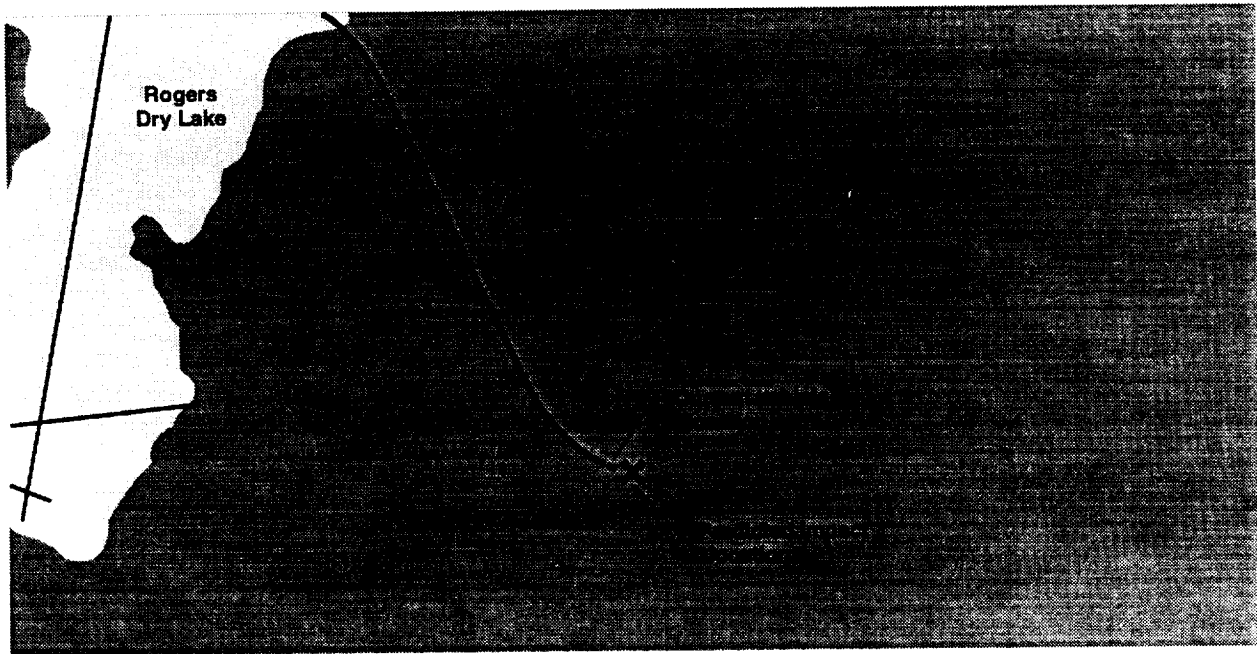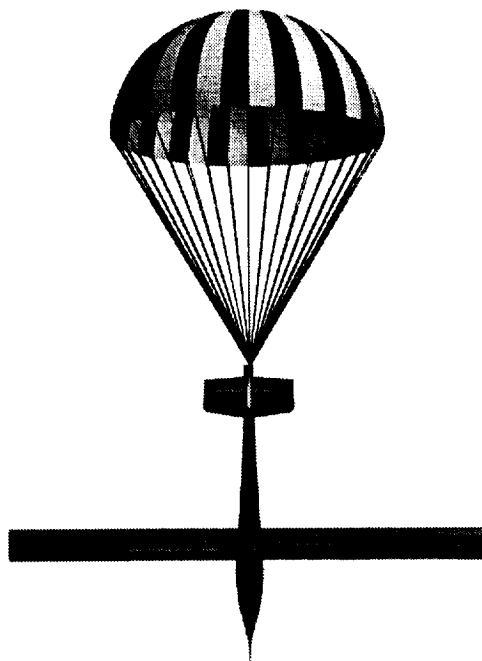
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Figure 4. ILEA code flowchart.

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Figure 5. Real-time display of impact location.

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(a) Parachute.

Figure 6. Termination techniques.

parachute, is the termination technique for which the ILEA was originally developed. For this technique, the parachute drag coefficient and reference area are known and can be used as inputs.

Figure 6(b) shows the use of a "termination" parachute to apply an asymmetric drag force to the vehicle. The parachute is of sufficiently small size to allow the vehicle to continue to fly in a descending turn to the ground. This technique is different from the previous illustration in that the aerodynamic surfaces are still generating lift. This type of termination technique generally results in much slower descent rates than any of the other techniques.

The inputs for the real-time algorithm in this case are derived by using the batch algorithm. Because the descent rate is known, an equivalent coefficient of drag, Cd, and a drag reference area, S, are determined by iteration until the correct descent rate is obtained. Downrange flight (or the distance covered as a result of the aerodynamic surfaces still flying) is not accounted for because the vehicle is descending in a constant turn. The predicted impact point does not account for the radius of the turn.

Figure 6(c) shows a termination technique that uses the vehicle control surfaces to put the vehicle into a spin. This system is modeled in the same manner as the flying descent technique described above. Although the spinning vehicle may have a nonzero lift-to-drag ratio, the turn radius is small. Predicting the heading of any downrange travel associated with the nonzero lift-to-drag ratio is well beyond current capabilities. Such travel is assumed to be random in nature and the net result small. In either case, the effects of the wind are expected to dominate.

Another common system is a combination termination/recovery system (fig. 6(d)). This type of termination technique is a modification of the technique shown in figure 6(a). Upon receiving the termination command, a drogue parachute is deployed from the vehicle that puts the vehicle into a rapid descent. At a predetermined altitude, a larger recovery parachute is deployed. The recovery parachute greatly slows the
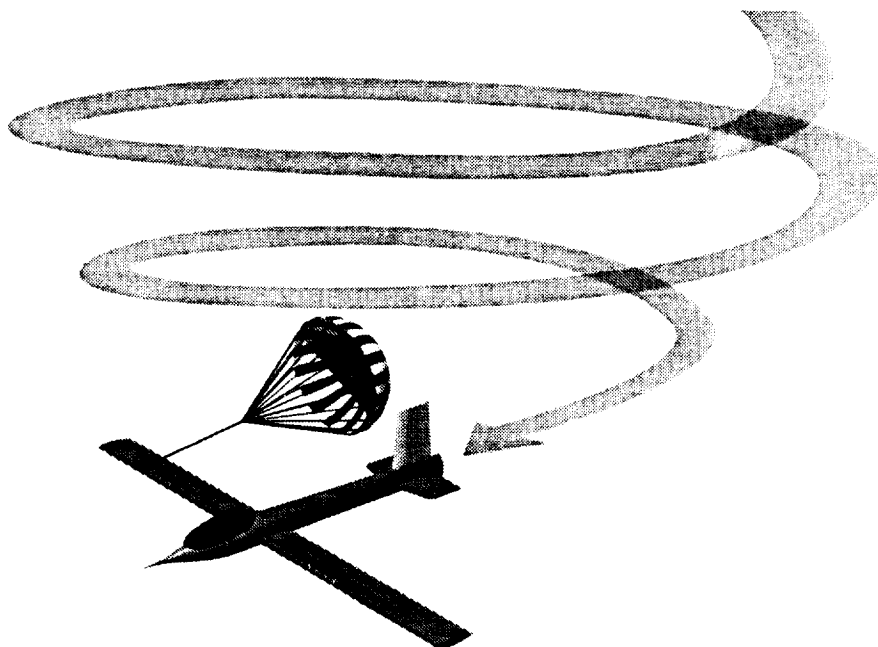
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(b) Asymmetric drag.

Figure 6. Continued.
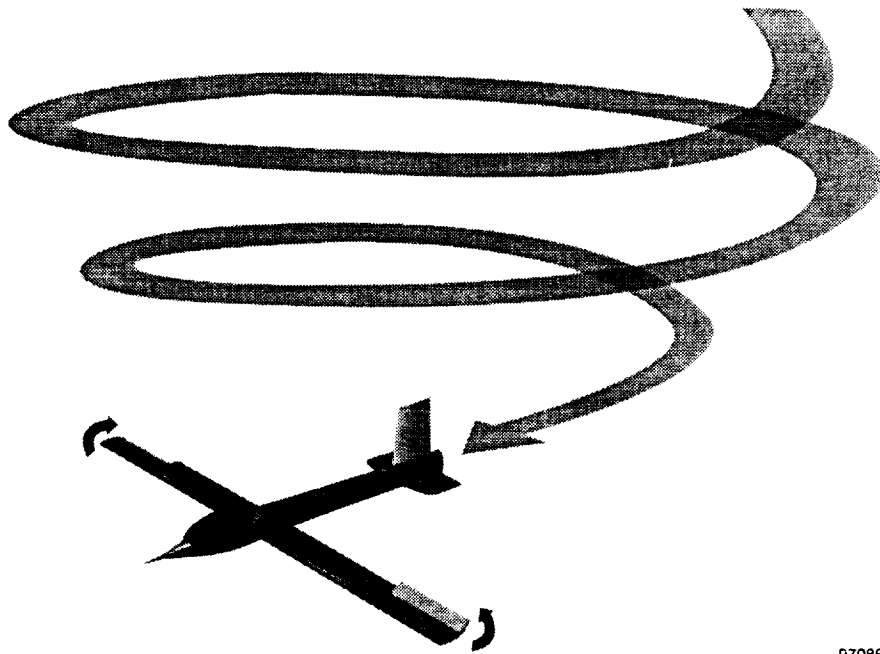
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(c) Control surface.

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(d) Two-stage parachute system.

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Figure 6. Concluded.

descent so that less damage will occur to the vehicle upon ground impact. This system is handled in two ways. The first way is to use the real-time algorithm, ignoring the effects of the drogue parachute and modeling only the main parachute. This modeling is done by inp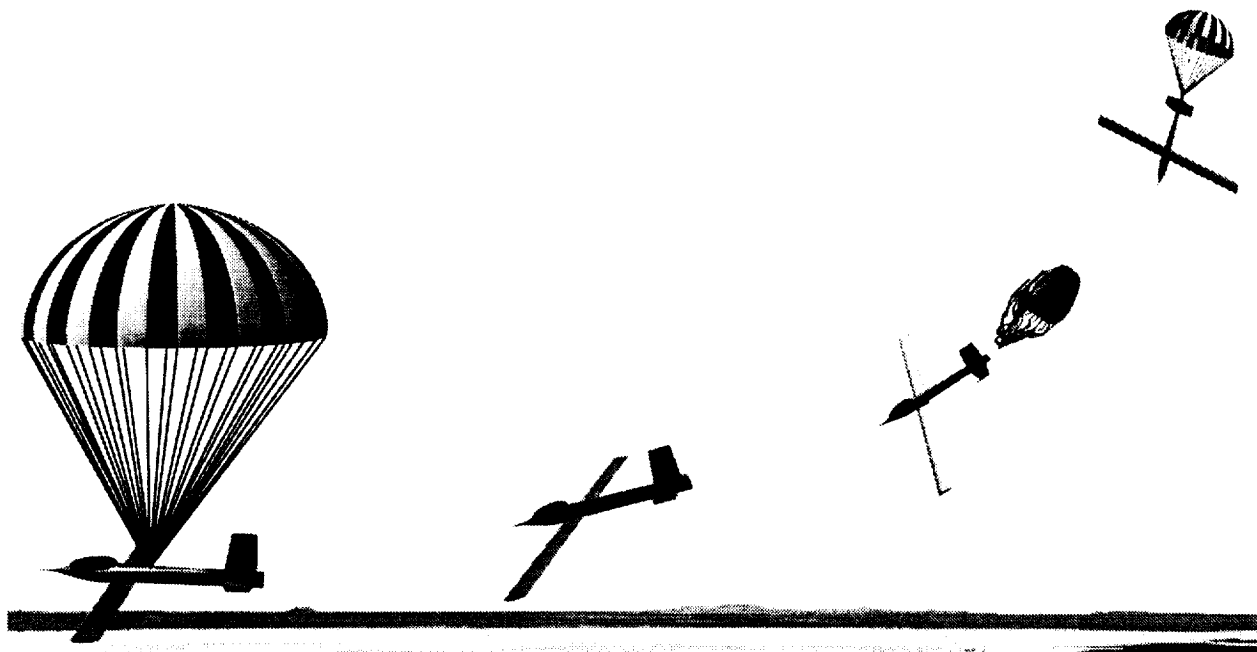utting only the drag coefficient and reference area of the main parachute, and zeroing the wind magnitude above the altitude at which the main parachute deploys. An analysis using the batch algorithm showed a majority of the vehicle drift occurred under the main parachute (fig. 7). This approach has been selected based on this analysis. These results are dependent on the relative sizes of the two parachutes and the altitude at which the larger parachute is deployed.

The second way is to use the batch algorithm to generate a plot that includes the effects of both parachutes (fig. 8). The plot shows the predicted downrange drift distance as a function of altitude. The RSO knows the current altitude of the vehicle and uses the plot to determine the expected impact location relative to the current location of the vehicle. This approach can be used for a single-parachute system as well.

Some vehicles can be expected to break up as a result of an FTS activation. As discussed earlier, only the most massive piece is modeled in the real-time ILEA; therefore, the vehicle weight in the terminated state is less than the total vehicle weight. The batch algorithm is used to estimate the drift of the other pieces. This estimation provides debris field bounds. That information is used to carefully plan the flightpath of the vehicle. The RSO can use the information during a flight to provide an additional buffer to any boundaries.

The real-time ILEA currently uses tracking radar and the GRIM display in the NASA Dryden control room. When using these facilities is not possible, or in the event of a display malfunction, the batch algorithm is used to generate a plot of drift distance as a function of altitude (fig. 8). The RSO can access vehicle altitude and position information from the vehicle command and control facility. With this
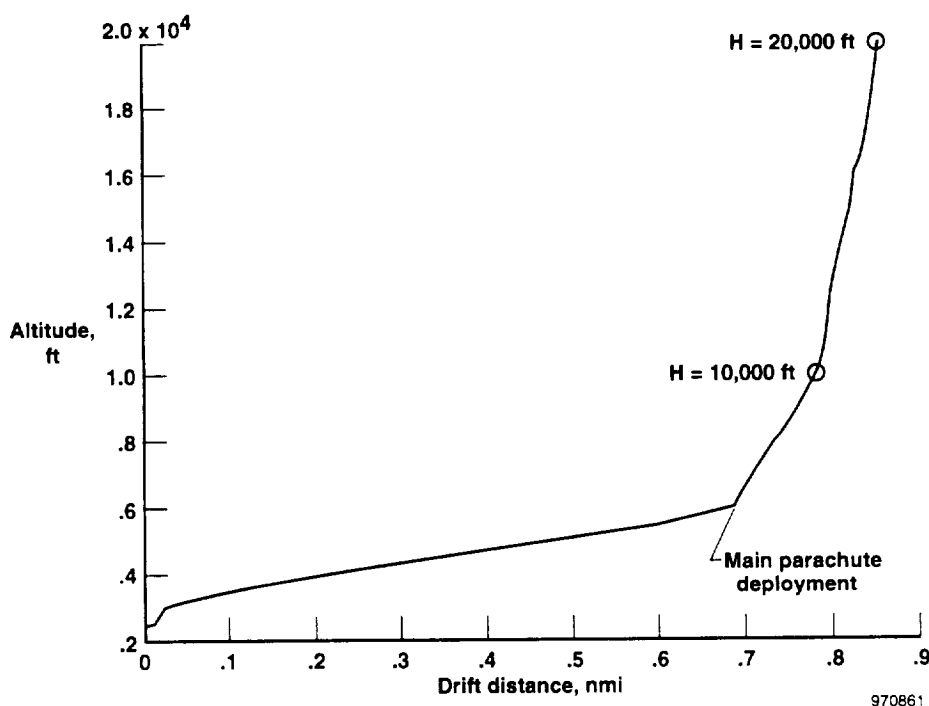

Figure 7. Drift distance with the multiparachute termination technique.
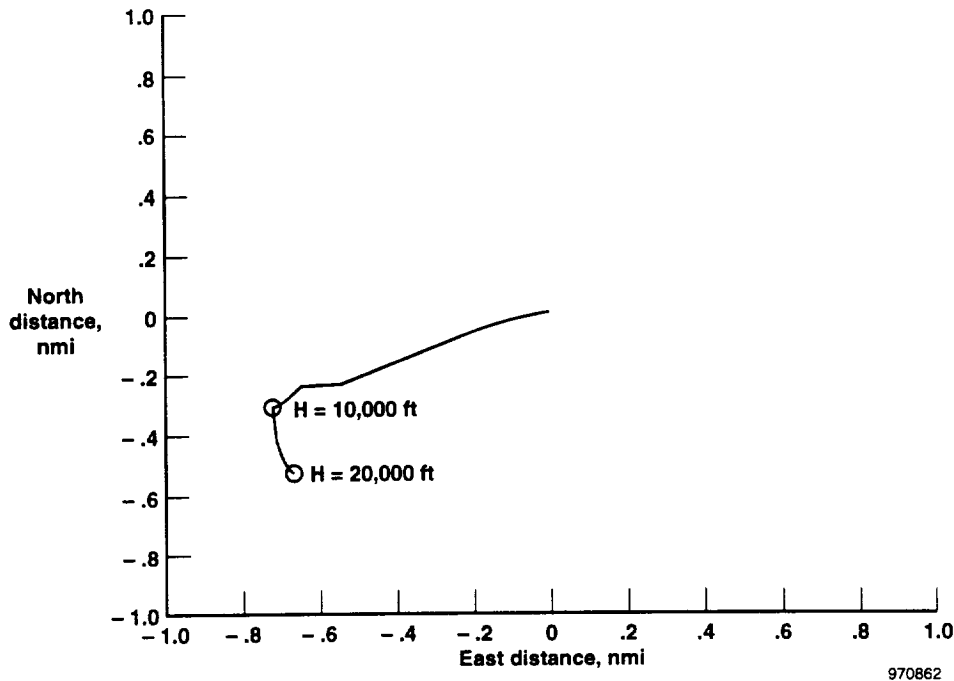
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Figure 8. Impact location as a function of termination altitude with the multiparachute technique.

information, predicting the impact location and safely conducting the mission is possible without the real-time display.

The ILEA is also used in real time for vehicles that follow preprogrammed flightpaths or are autonomous. In these cases, however, options for redirecting the flightpath are limited. The batch ILEA is used during mission planning before flight to estimate drift distances under various wind conditions, and buffer zones are applied to all boundaries. The vehicle flightpath is then constructed to avoid those buffer zones.

PROCEDURAL USE OF THE IMPACT-LOCATION ESTIMATION ALGORITHM

The RSO is responsible for ensuring the vehicle operation is within the airspace provided for the mission and, in the event of termination, avoiding damage to any ground assets by the vehicle. The real-time ILEA provides continuous information to the RSO on the predicted impact location of the vehicle if the FTS is activated.

The purpose of the FTS is to keep the vehicle within the designated airspace or range. The FTS is not intended to serve as a vehicle recovery system, although some designs serve both functions. If a vehicle breaks up over the range in an area that does not represent a hazard to any ground assets, the RSO does not need to activate the FTS. Activation of the system under such conditions, however, may be warranted in order to lessen the severity of the impact and spread of debris. The advantage the ILEA provides is the ability to make the termination decision with confidence that the vehicle will not drift into a sensitive area. In fact, termination can be delayed in order to clear a ground asset. When the FTS has been activated, the ILEA continues to update the predicted impact point (if accurate altitude data are still

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available). This update minimizes the effects of uncertainties associated with an assumed descent rate based on the termination technique and is useful in conducting recovery operations (although little can be done to affect the impact point).

Because the ILEA provides an estimate of the impact location, the RSO uses judgment to provide additional separation between the estimated impact location and various boundaries. For example, more margin would be provided around a boundary that represents a ground asset than around a boundary that indicates airspace or property limits. Information that would influence the RSO's decision regarding how much margin to provide includes whether the direction of drift is towards or away from a keep-out zone, the vehicle altitude, the termination technique, the degree of confidence in the assumed descent rate, and the time since the last wind update.

DISCUSSION

The algorithm has been adopted by several UAV operators who use it in their command and control stations. This use provides redundancy with the NASA Dryden control room in the event of a display failure. The simplicity of the algorithm (approximately 240 lines of code) allows its incorporation with even modest equipment.

The algorithm has evolved while in use at NASA Dryden. In the first release of the code, an estimate was made of the 1-g glide distance of the vehicle. A similar display was used in the X-15 program and was referred to as the energy cardioid.[8] The display was used to show which lakebeds were within gliding distance in the event of an emergency. For the present application, it was reasoned that if the FTS system should fail, knowing how far the vehicle could travel would be good. Given the altitudes at which the aircraft are designed to operate and the fact that most of them resemble sail planes with very high lift-to-drag ratios, the predicted glide distances are quite large—in some cases consisting of much of the western United States. The assumption that the vehicle could glide those long distances was judged to be unreasonable. If a failure occurs that prevents normal command and control and termination, the vehicle is unlikely to be able to maintain trim over the speed and altitude band required to reach such far destinations. In addition, the areas were too large to provide useful information to the RSO, so this feature was eliminated.

Modeling the vehicle equations of motion was initially thought to be required to account for the kinetic energy of the vehicle along the flightpath. Simulations showed that for vehicles traveling at subsonic speeds, kinetic energy is insignificant when compared to the effects of the wind as the vehicle descends. In addition, the termination systems tend to rapidly eliminate the forward velocity of the vehicle upon activation. The equations of motion can provide a better estimate for termination techniques that result in rapid descent rates or for situations where terminal velocity is not reached. Because the systems modeled result in slow descent rates, terminal velocity is reached quickly, and the complication associated with modeling the equations of motion is not necessary.

Using the equations of motions to rigorously model the vehicle descent is straightforward. With the level of uncertainty associated with the assumptions and inputs, however, additional accuracy obtained through such an approach is believed to be insignificant. The added computation requirements may strain the ability of some systems to perform the necessary computations in a real-time environment, particularly systems that are performing other real-time tasks during the mission.

RESULTS

Only one activation of a vehicle FTS has occurred since the ILEA has been in use. The vehicle used a ballistic parachute termination system (fig. 6(a)). While descending, the vehicle began to break up (its wing separated because of structural failure) at an altitude of approximately 29,400 ft. At an altitude of approximately 18,400 ft, the FTS was activated. At an altitude of approximately 16,200 ft, the parachute blossomed and the vehicle descended to ground impact. At an altitude of 3400 ft, altitude information on the vehicle was lost because of radar look-angle obstructions.

The actual impact location was approximately 0.6 mi from the impact point predicted when the FTS system was activated. Debris was scattered along a path approximately 2.5 mi long. The debris furthest from the main wreckage was the wing section and associated components that departed before FTS activation. The debris field for the pieces under parachute was distributed along a line approximately 150 ft in length where the vehicle was dragged along the ground. The ILEA did its job well in that it informed the RSO that no ground assets were in the area and none were in the direction of drift.

The discrepancy in impact location can be attributed to a number of factors. The primary contributor is the result of a change in the winds. Had the best available wind information been included in the algorithm, the predicted impact point would have been less than 0.1 mi from the actual impact point. More accurate wind information was available only after the accident as a result of the detailed accident investigation that ensued. At the time of the accident, wind updates were generally not made during the mission.

Because the vehicle broke up, the weight of the vehicle under parachute was different from that assumed by the model. Despite the weight differences, the actual descent rate closely matched the assumed descent rate. The vehicle was in a vertical descent when the FTS was activated. This vertical descent is consistent with the assumption that the forward velocity of the vehicle will dissipate quickly and not influence the final results in a significant way.

After the successful utilization of the algorithm in the above situation, the algorithm was tested to see how it would perform in an off-design case. The case selected was an accident involving the X-31 research aircraft. The X-31 aircraft is a full-scale, piloted, fighter-class vehicle that uses thrust vectoring for agility at high-angle-of-attack flight conditions.[9] The vehicle weighs approximately 16,500 lbf and has a cruise speed of 300 kn.

The X-31 case violates several assumptions used in developing the model for the ILEA. The X-31 postdeparture dynamics were not expected to match the UAV model. In spite of that fact, the drift direction was accurately predicted and after correcting for "non-UAV, post-FTS" behavior, the impact point was predicted within 0.25 mi. Appendix B provides a detailed discussion of this case.

CONCLUDING REMARKS

An impact-location estimation algorithm (ILEA) has been developed and is in use at NASA Dryden Flight Research Center that estimates the impact location for subsonic (low-energy) uninhabited aerial vehicles. The algorithm accounts for the most recently observed winds and the descent rate of the vehicle. The ILEA has the flexibility to account for a variety of termination techniques and is computationally simple. The algorithm operates well in the real-time flight test environment.

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Despite the simplistic model used by the ILEA, the results are adequate to perform the range safety function in an area that contains high-value ground assets that must be avoided in the event of termination. The algorithm has been used successfully in an actual flight termination, predicting the impact point to within 0.6 mi of the actual impact location. The ILEA has been adapted by several uninhabited aerial vehicle operators for use in their command and control facilities and has been included in real-time displays by other ranges.

APPENDIX A
FORTRAN CODE

The code for one of the batch versions of the impact algorithm is as follows.

```
      PROGRAM Traj9
C
C     CALCULATES IMPACT POINT AS A FUNCTION OF ALTITUDE,
C     AIRSPEED, AND HEADING FOR A GIVEN ALTITUDE
C
c           Originally written by Brent Cobleigh.
c           Modified by Elise Gravance and Jeff Bauer.
c           Last modified December 3, 1996 by Jeff Bauer.
C
      DIMENSION VX(100),VY(100),
     .     WINDMAG(100),WINDDIR(100),HVT(11),
     .     ALT(100),DIR(100),DENSITY(100),CHDTIME(100),
     .     SPD(100),ALTH(100),XHDOT(100),RHORTO(100)
      COMMON /DATA/ ICOUNT,ALTDOT,DIRECTION,XMAG,RHO,
     .     ALTH,XHDOT,CTRALT,ALT,SPD,RHORTO,DIR,
     .     WEIGHT,CHALTDOT,SCD,VVCURR,DENSITY,PLD,
     .     VVLOW,VVHIGH,BPALT,CURDENS,CURALT,
     .     HVT

C     AIR DENSITY*1000 FROM ALTITUDE = 0 TO 99,000 FT IN 1000-FT
C     INCREMENTS
C
      DATA DENSITY /2.3769,2.3081,2.2409,2.1752,2.1110,2.0482,
     .  1.9869,1.9270,1.8685,1.8113,1.7556,1.7011,1.6480,
     .  1.5961,1.5455,1.4962,1.4480,1.4011,1.3553,1.3107,
     .  1.2673,1.2249,1.1836,1.1435,1.1043,1.0663,1.0292,
     .  .99311,.95801,.92387,.89068,.85841,.82704,.79656,
     .  .76696,.73820,.71028,.67800,.64629,.61608,.58727,
     .  .55982,.53365,.50871,.48493,.46227,.44067,.42008,
     .  .40045,.38175,.36391,.34692,.33072,.31527,.30055,
     .  .28652,.27314,.26039,.24824,.23665,.22561,.21508,
     .  .20505,.19548,.18336,.17767,.16938,.16148,.15395,
     .  .14678,.13993,.13341,.12719,.12126,.11561,.11022,
     .  .10258,.09770,.09306,.08865,.08445,.08046,.07665,
     .  .07304,.06960,.06632,.06321,.06024,.05742,.05473,
     .  .05217,.04974,.04742,.04521,.04311,.04111,.03920,
     .  .03739,.03566,.03401/

C     DRAG CHUTE PARAMETER SCD=(CHUTE AREA)(CHUTE DRAG COEFFICIENT)
C
C     Open output files
C
      OPEN(UNIT=7,FILE='output',status='unknown')
      OPEN(UNIT=11,FILE='crash',STATUS='UNKNOWN')
C
C     READ IN CURRENT WINDS FROM FILE WIND.DAT
C
      CALL READWIND
```

```
C
C   INPUT CURRENT ALTITUDE, CALIBRATED AIRSPEED, HEADING,
C   GROUND SPEED, WEIGHT, AND CdS
C
      PRINT*,'INPUT AIRCRAFT ALTITUDE (FT)'
      READ(*,*) CURALT
      PRINT*,'INPUT AIRCRAFT WEIGHT (LB)'
      READ(*,*) WEIGHT
         rmass = weight/32.174
      PRINT*,'INPUT AIRCRAFT CdS (FT^2)'
      READ(*,*) SCD
c         write(7,*)'Alt, Airspd, Heading, Ground Spd, Weight, mass, SCd'
c         write(7,*)curalt,vt,theta,vg,weight,rmass,scd


C   CALCULATE TIME TO PASS THROUGH EACH ALTITUDE BAND
C   USE ALTITUDE BANDS OF 1000 FT
C
      GRDALT=2372.   ! GROUND ALTITUDE AT EDWARDS
      ALT1=GRDALT    ! ALTITUDE BREAKPOINT
      ALT2=3000.     ! ALTITUDE BREAKPOINT
      ICOUNT=0
         Time=0.0       ! Time to impact from altitude
CC
      DO WHILE (ALT1.LT.CURALT)
      ICOUNT=ICOUNT+1            ! DUMMY COUNTER
      DALT=ALT2-ALT1
C
C   GET HDOT FOR THE CENTER OF THE CURRENT ALTITUDE BAND
C
      CTRALT=(ALT2-ALT1)/2 + ALT1    ! CENTER OF ALTITUDE BAND
c         write(7,*)'CTRALT =',ctralt

      CALL HDOT                 ! INTERPOLATE HDOT
      CHDTIME(ICOUNT)=DALT/CHALTDOT   ! CALCULATE TIME IN Alt BAND
      TIME=Time + chdtime(icount)

      CALL WINDD                ! INTERPOLATE WIND DIRECTION
      WINDDIR(ICOUNT)=DIRECTION
      CALL WINDM                ! INTERPOLATE WIND MAGNITUDE
      WINDMAG(ICOUNT)=XMAG*1.69     ! CONVERT MAGNITUDE TO FT/SEC
C
C   INCREMENT ALTITUDE BAND BY 1000 FEET
C
      ALT1=ALT2
      ALT2=ALT2+1000.
         IF (ALT2.GT.CURALT) THEN
             ALT2=CURALT
         ENDIF
      END DO
C
C   COMPUTE IMPACT POINT
C
      DO 200 J=1,ICOUNT
C
C   CALCULATE X & Y GROUND TRACK VELOCITY ONLY SUBJECT TO WINDS ALOFT
```

```
C
      XWINDHD=(270.-WINDDIR(J))      ! WIND HEADING
      VX(J)=WINDMAG(J)*COS(XWINDHD/57.3)
      VY(J)=WINDMAG(J)*SIN(XWINDHD/57.3)
  200 CONTINUE
C
C     CALCULATE X & Y GROUND TRACK DISTANCE FROM START
C
      XDIST=0.
      YDIST=0.

      DO 210 K=1,ICOUNT
      XDIST=XDIST+VX(K)*CHDTIME(K)
      YDIST=YDIST+VY(K)*CHDTIME(K)
  210 CONTINUE
C
C     CALCULATE TOTAL DISTANCE TRAVELLED
C
      DISTANCE=SQRT(XDIST**2+YDIST**2)
C
C     WRITE RESULTS TO OUPUT FILES
C
      write(7,*)'Time =',time
      write(11,*)'East (ft), North (ft), Total Distance (ft)'
      WRITE (11,140) XDIST,YDIST,DISTANCE
  140 FORMAT (3(F12.2,',',))
      CLOSE(7)
      CLOSE(11)
      STOP
      END
*****************************************************************
      SUBROUTINE HDOT
C
C     CALCULATES CHUTE HDOT AT GIVEN ALTITUDE
C
      DIMENSION HVT(11),
     .      ALT(100),DIR(100),DENSITY(100),
     .      SPD(100),ALTH(100),XHDOT(100),RHORTO(100)
      COMMON /DATA/ ICOUNT,ALTDOT,DIRECTION,XMAG,RHO,
     .      ALTH,XHDOT,CTRALT,ALT,SPD,RHORTO,DIR,
     .      WEIGHT,CHALTDOT,SCD,VVCURR,DENSITY,PLD,
     .      VVLOW,VVHIGH,BPALT,CURDENS,CURALT,
     .      HVT
C
C     INTERPOLATE DENSITY AT CURRENT ALT
C
      DO 10 I=1,100
      DUMALT2=REAL(I) *1000.
      DUMALT1=REAL(I-1)*1000.
C
      IF ((DUMALT2.GT.CTRALT).AND.(CTRALT.GE.DUMALT1)) THEN
          CURDENSITY=(CTRALT-DUMALT1)/(DUMALT2-DUMALT1)*
     .          (DENSITY(I+1)-DENSITY(I))+DENSITY(I)
          CURDENS=CURDENSITY/1000.
          GOTO 30
```

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```
      ENDIF
C
   10 CONTINUE
C
C  CALCULATE CHUTE ALTITUDE RATE FROM EQUATION QBAR*S*CD=WEIGHT
C  WHERE QBAR=.5*CURDENS*V**2
C
   30 Continue
      CHALTDOT=SQRT(2*WEIGHT/CURDENS/SCD)
      RETURN
      END
************************************************************
      SUBROUTINE READWIND
C
C  READ IN CURRENT WINDS FILE
C
      DIMENSION HVT(11),
     .     ALT(100),DIR(100),DENSITY(100),
     .     SPD(100),ALTH(100),XHDOT(100),RHORTO(100)
      COMMON /DATA/ ICOUNT,ALTDOT,DIRECTION,XMAG,RHO,
     .     ALTH,XHDOT,CTRALT,ALT,SPD,RHORTO,DIR,
     .     WEIGHT,CHALTDOT,SCD,VVCURR,DENSITY,PLD,
     .     VVLOW,VVHIGH,BPALT,CURDENS,CURALT,
     .     HVT

      OPEN(UNIT=8,FILE='wind.dat',STATUS='OLD')
      DO 20 I=1,100
      READ(8,*) ALT(I),DIR(I),SPD(I),dens
      IF(ALT(I).LT.1) THEN
          GOTO 30
      ENDIF
   20 CONTINUE
   30 CLOSE(8)
      END
************************************************************
      SUBROUTINE WINDD
C
C  INTERPOLATES WIND DIRECTION FROM FILE
C
      DIMENSION HVT(11),
     .     ALT(100),DIR(100),DENSITY(100),
     .     SPD(100),ALTH(100),XHDOT(100),RHORTO(100)
      COMMON /DATA/ ICOUNT,ALTDOT,DIRECTION,XMAG,RHO,
     .     ALTH,XHDOT,CTRALT,ALT,SPD,RHORTO,DIR,
     .     WEIGHT,CHALTDOT,SCD,VVCURR,DENSITY,PLD,
     .     VVLOW,VVHIGH,BPALT,CURDENS,CURALT,
     .     HVT
      DO 10 I=1,100
   IF ((ALT(I+1).GT.CTRALT).AND.(CTRALT.GE.ALT(I))) THEN

      IF (ABS(DIR(I+1)-DIR(I)).LT.90.) THEN
          DIRECTION=(CTRALT-ALT(I))/(ALT(I+1)-ALT(I))*
     .         (DIR(I+1)-DIR(I))+DIR(I)
      ELSEIF ((DIR(I+1).LE.180.).AND.(DIR(I).LE.180.)) THEN
```

```
      DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DIR(I))+DIR(I)
ELSEIF ((DIR(I+1).LE.270.).AND.(DIR(I).LE.270.).AND.
.       (DIR(I+1).GT.90.).AND.(DIR(I).GT.90.)) THEN
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DIR(I))+DIR(I)
ELSEIF ((DIR(I+1).LE.360.).AND.(DIR(I).LE.360.).AND.
.       (DIR(I+1).GT.180.).AND.(DIR(I).GT.180.)) THEN
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DIR(I))+DIR(I)

ELSEIF ((DIR(I+1).LE.360.).AND.(DIR(I+1).GT.270.).AND.
.       (DIR(I).GE.0.).AND.(DIR(I).LT.90.)) THEN
  DUMDIR=DIR(I)+360.
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DUMDIR)+DUMDIR
  IF(DIRECTION.GE.360.) DIRECTION=DIRECTION–360.
ELSEIF ((DIR(I).LE.360.).AND.(DIR(I).GT.270.).AND.
.       (DIR(I+1).GE.0.).AND.(DIR(I+1).LT.90.)) THEN
  DUMDIR=DIR(I+1)+360.
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DUMDIR–DIR(I))+DIR(I)
  IF(DIRECTION.GE.360.) DIRECTION=DIRECTION–360.

ELSEIF ((DIR(I).LE.270.).AND.(DIR(I).GT.180.).AND.
.       (DIR(I+1).GE.0.).AND.(DIR(I+1).LT.90.)) THEN
  IF ((DIR(I)-DIR(I+1)).LE.180.) THEN
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DIR(I))+DIR(I)
ELSE
  DUMDIR=DIR(I+1)+360.
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DUMDIR–DIR(I))+DIR(I)
ENDIF
ELSEIF ((DIR(I+1).LE.270.).AND.(DIR(I+1).GT.180.).AND.
.       (DIR(I).GE.0.).AND.(DIR(I).LT.90.)) THEN
  IF ((DIR(I+1)–DIR(I)).LE.180.) THEN
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DIR(I))+DIR(I)
ELSE
  DUMDIR=DIR(I)+360.
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DUMDIR)+DUMDIR
ENDIF

ELSEIF ((DIR(I).LE.360.).AND.(DIR(I).GT.270.).AND.
.       (DIR(I+1).GE.90.).AND.(DIR(I+1).LT.180.)) THEN
  IF ((DIR(I)–DIR(I+1)).LE.180.) THEN
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DIR(I+1)–DIR(I))+DIR(I)
ELSE
  DUMDIR=DIR(I+1)+360.
        DIRECTION=(CTRALT–ALT(I))/(ALT(I+1)–ALT(I))*
.       (DUMDIR–DIR(I))+DIR(I)
  IF (DIRECTION.GE.360.) THEN
```

```
          DIRECTION=DIRECTION-360.
             ENDIF
          ENDIF
       ELSEIF ((DIR(I+1).LE.360.).AND.(DIR(I+1).GT.270.).AND.
      .       (DIR(I).GE.90.).AND.(DIR(I).LT.180.)) THEN
        IF ((DIR(I+1)-DIR(I)).LE.180.) THEN
            DIRECTION=(CTRALT-ALT(I))/(ALT(I+1)-ALT(I))*
      .       (DIR(I+1)-DIR(I))+DIR(I)
        ELSE
         DUMDIR=DIR(I)+360.
            DIRECTION=(CTRALT-ALT(I))/(ALT(I+1)-ALT(I))*
      .       (DIR(I+1)-DUMDIR)+DUMDIR
         IF (DIRECTION.GE.360.) THEN
               DIRECTION=DIRECTION-360.
          ENDIF
          ENDIF
        ENDIF
       GOTO 20
       ENDIF
    10 CONTINUE
    20 RETURN
       END
C*****************************************************************
       SUBROUTINE WINDM
C
C    INTERPOLATES WIND MAGNITUDES
C
       DIMENSION HVT(11),
      .    ALT(100),DIR(100),DENSITY(100),
      .    SPD(100),ALTH(100),XHDOT(100),RHORTO(100)
       COMMON /DATA/ ICOUNT,ALTDOT,DIRECTION,XMAG,RHO,
      .    ALTH,XHDOT,CTRALT,ALT,SPD,RHORTO,DIR,
      .    WEIGHT,CHALTDOT,SCD,VVCURR,DENSITY,PLD,
      .    VVLOW,VVHIGH,BPALT,CURDENS,CURALT,
      .    HVT
C    INTERPOLATE WIND MAGNITUDE
C
       DO 10 I=1,100
       IF ((ALT(I+1).GT.CTRALT).AND.(CTRALT.GE.ALT(I))) THEN
       XMAG=(CTRALT-ALT(I))/(ALT(I+1)-ALT(I))*
      .    (SPD(I+1)-SPD(I))+SPD(I)
       GOTO 21
       ENDIF
    10 CONTINUE
    21 RETURN
       END
```

APPENDIX B
X-31 AIRCRAFT DISCUSSION

On January 19, 1995, as the X-31 was returning from a research mission and descending at an altitude of 20,000 ft, a failure of the airdata system caused the vehicle to depart controlled flight and crash. Data from this accident were replayed through the real-time impact-location estimation algorithm (ILEA) to determine how well the impact point would have been predicted. The uncorrected results were disappointing, largely because of the nature of the departure.

For purposes of this investigation, the wind information used was obtained from a weather balloon launched approximately one-half hour after the accident. The winds for this case were very low, and errors in the prediction were not likely to have been a result of inaccurate wind data. Pilot ejection was considered as the flight termination system activation point. Because a prediction of the vehicle descent rate was not available beforehand, a descent rate was obtained by dividing the altitude loss (from ejection to impact) by the time from ejection to impact.

Ejection occurred at an altitude of approximately 20,500 ft above sea level. From this point, the ILEA predicted the impact would occur 597 ft to the north and 557 ft to the west of the ejection location. In actuality, the vehicle impacted approximately 4083 ft to the north and 2947 ft to the west. The primary contributor to this error is the postdeparture behavior of the aircraft.

During this departure, the vehicle gained approximately 800 ft in altitude before entering into altitude excursions varying as large as ±100 ft. The vehicle airspeed significantly decreased and the pilot ejected. As a result of the reduced airspeed, the vehicle righted itself following the pilot ejection and "flew" for approximately 20 sec in a north-northwestern direction. The vehicle continued to descend and gradually increase airspeed until it once again departed. This second departure resulted in a significantly larger altitude excursion than the previous one. The vehicle never recovered from this departure, and altitude excursions continued through the final descent. The engine continued to operate until impact.

This sequence violated two basic assumptions of the ILEA, the most significant being the approximately 20 sec of "flight" where the vehicle covered approximately 2430 ft to the north and 1470 ft to the west. This "flight" accounts for the majority of the error between the predicted and actual impact locations. The second assumption violated was that the vehicle would not accelerate in the vertical plane during the descent. Because the vehicle actually increased altitude during portions of the descent, this assumption was violated. When the "flight" distance between departures is subtracted, the drift direction was accurately predicted and the location was predicted to within approximately 0.25 mi.

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An impact-location estimation algorithm is being used at the NASA Dryden Flight Research Center to support range safety for uninhabited aerial vehicle flight tests. The algorithm computes an impact location based on the descent rate, mass, and altitude of the vehicle and current wind information. The predicted impact location is continuously displayed on the range safety officer's moving map display so that the flightpath of the vehicle can be routed to avoid ground assets if the flight must be terminated. The algorithm easily adapts to different vehicle termination techniques and has been shown to be accurate to the extent required to support range safety for subsonic uninhabited aerial vehicles. This paper describes how the algorithm functions, how the algorithm is used at NASA Dryden, and how various termination techniques are handled by the algorithm. Other approaches to predicting the impact location and the reasons why they were not selected for real-time implementation are also discussed.

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